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(54) **Wavelength addressed network of fibre optic interferometric sensors**

(57) Apparatus for the measurement of one or more physical parameters, comprising a radiation source 1, fibre optic sensing network 5 which comprises a plurality of sensing interferometers 10 each of which includes wavelength filter means for selecting a band of wavelengths 11 from the source means 1 and converting the magnitude of physical parameters to a change in a sensor optical path length delay; a reference interferometer 7 for selecting a reference optical path delay; a wavelength selection means 8 for selecting one or more of the band of wavelengths 11 filtered by one or more of the sensing interferometers 10; and detection means 120 for converting the radiation selected by the wavelength selector 8 to a electrical signal.

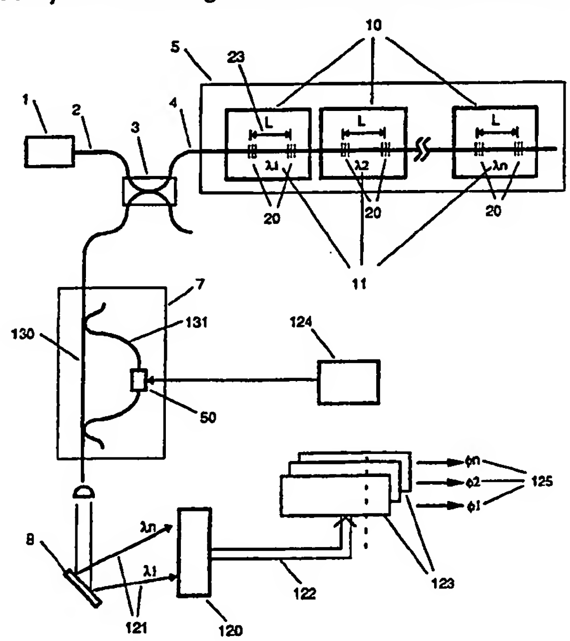

Figure 11

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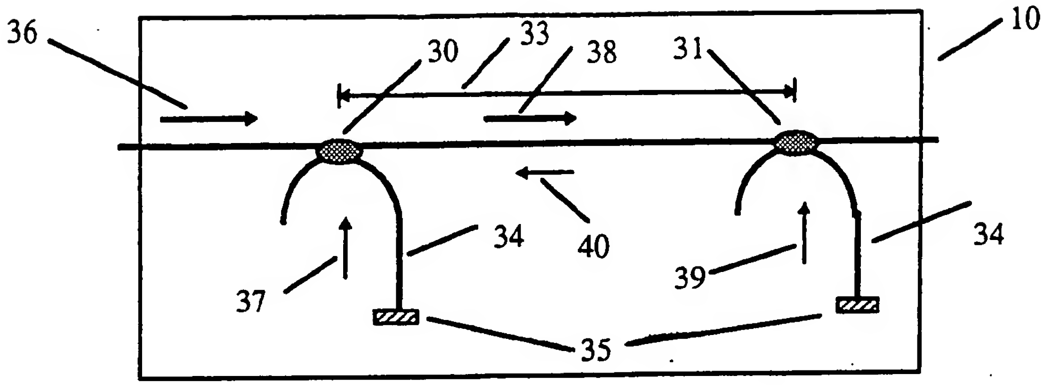

Figure 3

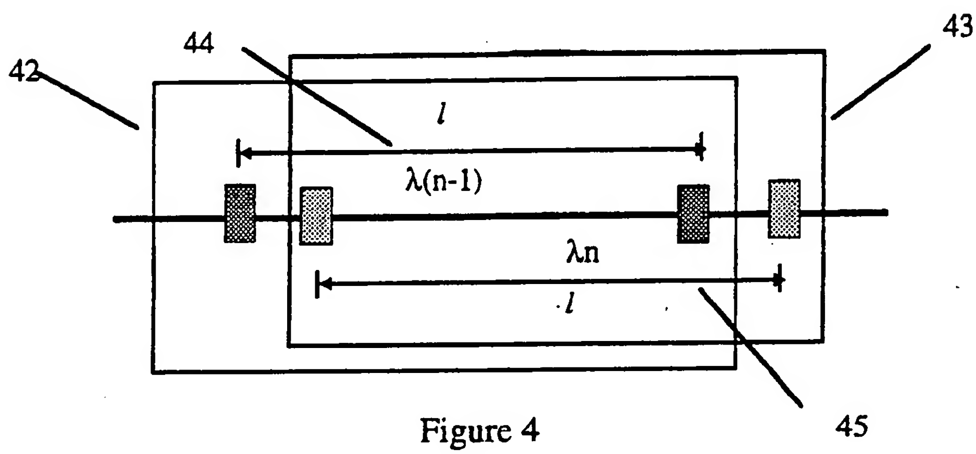

Figure 4

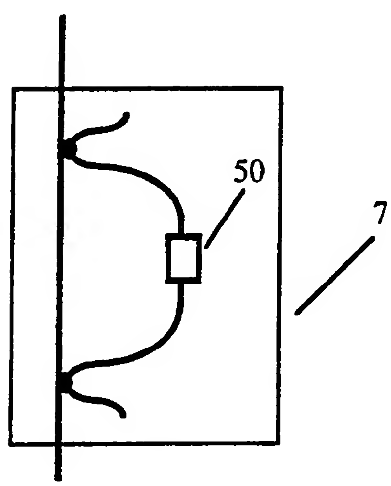

Figure 5

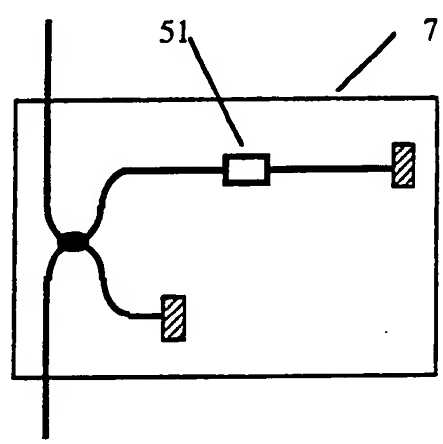

Figure 6

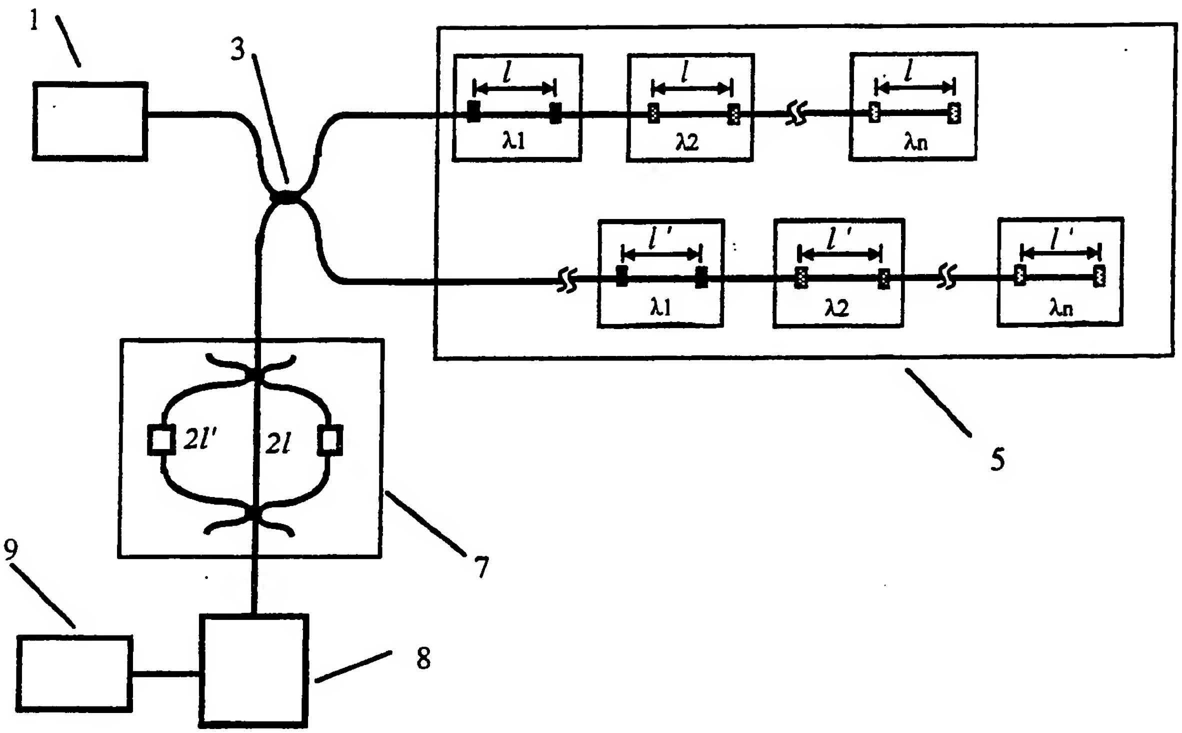

Figure 8

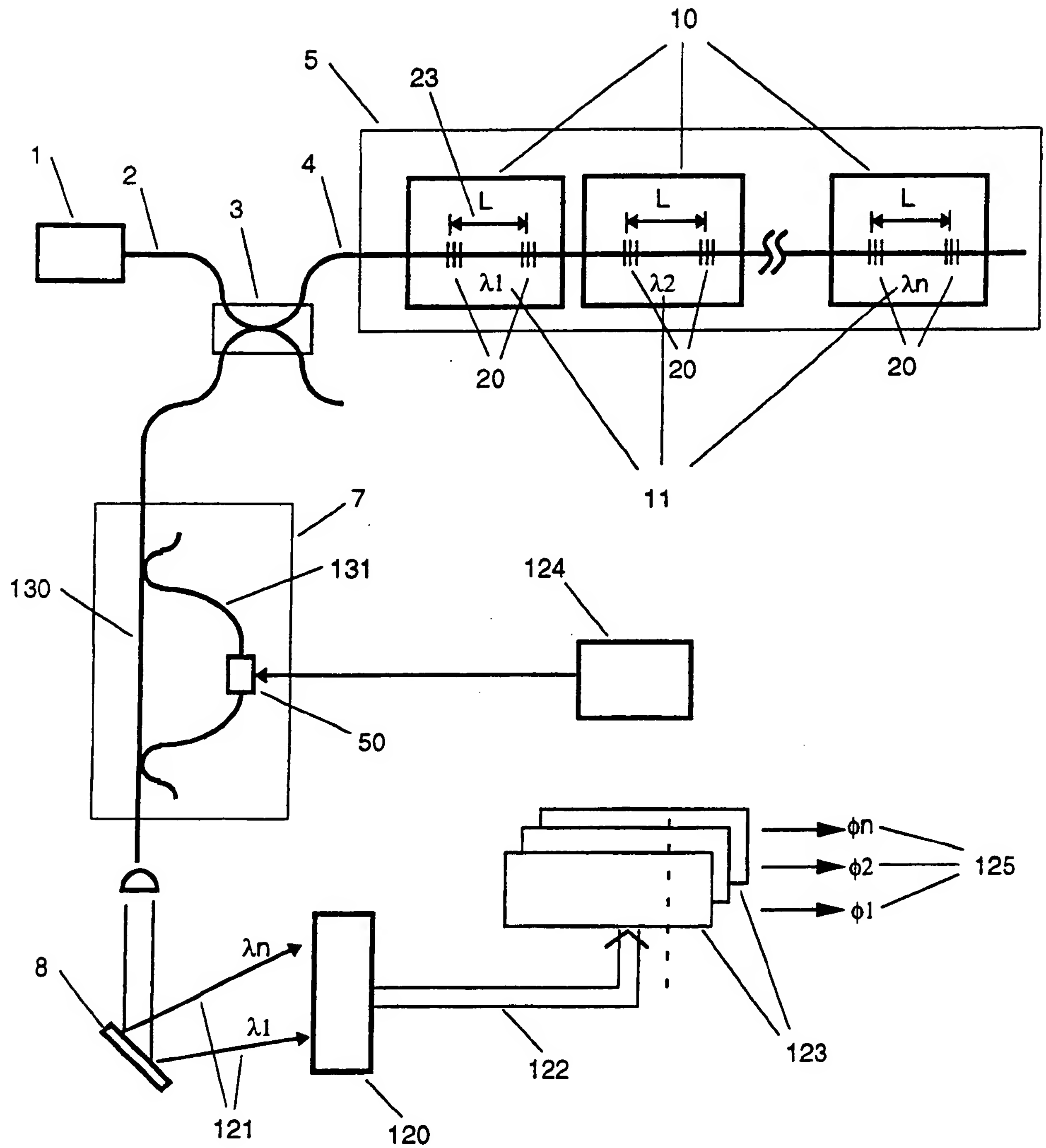
10
5
23
1
2
4
3
L
L
L
λ1
λ2
λn
20
20
20
11
7
130
131
124
50
φn
φ2
φ1
125
8
λn
λ1
121
120
122
123

Figure 11

high acoustic frequencies. Wavelength-multiplexed arrays using scanned laser sources can only interrogate sensors on a sequential basis and are therefore unsuitable for real-time sensing from an array unless the frequency of acoustic detection is very low, allowing sampling of signals at twice the acoustic frequency, or greater, in order to satisfy the well-known Nyquist sampling criterion. Use of multiple optical sources, each being modulated, and each being of different wavelength, is, of course, possible, but represents an expensive option for large arrays.

The object of the current invention is a multiplexed system which uses the technique of "Spectral slicing" of the energy emitted by a broadband source to divide the available energy into a number of separate spectral regions, each spectral region being used for interrogation of a separate interferometric sensor element. Thus in one implementation each interferometer in the array contains a narrow band optical filter to define a narrow spectral band for each sensor interferometric element. This filter acts in combination with the normal periodic light transmission function of the interferometer to constrain operation of the interferometer to the narrow spectral range defined by this additional filter. The light reflected from, or transmitted by, the sensor/filter combinations is then fed to a balancing interferometer which substantially compensates for the path imbalance in the sensor interferometer and can also incorporate a phase or frequency modulating element in one of its light paths to allow heterodyne signal processing of the sensor output. The light output of this receiving interferometer is then fed into a spectrometer to separate light substantially lying within each narrow spectral band, corresponding to each sensor in the array, before directing it onto an optical detector array. Each of the signals from each element of this detector array may then be processed, for example by phase or frequency demodulation of the detected heterodyne signal, to recover an electronic analogue of the acoustic signal affecting the acoustic sensor equipped with the filter of wavelength corresponding to that channel in the receiver spectrometer.

This invention makes use of a number of well-established techniques such as wavelength division multiplexing, sensing array networks, heterodyne detection, matched interferometers, and wavelength demultiplexing onto parallel detector arrays. It is the combination of these state-of-the-art techniques to provide the only-known practical solution to the demanding problem of simultaneous acquisition of high-bandwidth information in very-long arrays

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The wavelength filter means may be a wavelength selective grating inside an optical fibre waveguide, or may be a wavelength selective optical fibre coupler, or may be an integrated optic grating device.

The sensing interferometer means may comprise a pair of wavelength filter means which may be optical fibre gratings having similar wavelength responses separated by a short length of fibre which is sensitised to the measurand.

The reference interferometer means may be an interferometer in a Mach Zehnder configuration, or may be an interferometer in a Michelson configuration. The reference interferometer may also be constructed partly or entirely such that the electromagnetic radiation is confined within optical fibre. In addition a frequency shifter such as an acoustic optic modulator or a fibre optic frequency shifter may be put in one or more paths of the reference interferometer means to provide a means for heterodyne detection or alternatively, a phase modulator, such as an electro-optic modulator or a fibre wound around a piezo-electric transducer, may be used in one or more paths in the reference interferometer means to provide a means for synthetic heterodyne detection.

The sensing interferometer means may be arranged in an order which optimises the signal to noise ratio of the system.

The wavelength selection means may be an optical spectrum analyser, a monochromator, an optical filter wheel, an optical grating, or one or more optical fibre gratings matched to the wavelength range of the wavelength filter means and may be connected in series with an optical fibre coupler to direct each selected wavelength range to a detector.

The detection means may be a linescan camera or may be an array of discrete detectors.

In an embodiment of the present invention, the apparatus is one in which the electromagnetic radiation utilised in the apparatus is conveyed between one or more of the different components of the apparatus by one or more optical fibre waveguides.

In an embodiment of the present invention, the apparatus is one in which there is provided a sensing network means of interconnected optical fibre sensing interferometer means, each sensing

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 is a diagram of an embodiment of the present invention, in which optical fibres are used and the sensing network means is used in reflection;

Figure 2 is a diagram of an embodiment of the sensing interferometer means;

Figure 3 is a diagram of an embodiment of the sensing interferometer means using wavelength selective couplers;

Figure 4 is a diagram of an embodiment of part of the sensing network means in which two sensing interferometer means overlap;

Figure 5 is a diagram of an embodiment of the reference interferometer means taking the form of a Mach-Zehnder interferometer;

Figure 6 is a diagram of an embodiment of the reference interferometer means taking the form of a Michelson interferometer;

Figure 7 is a diagram of a preferred embodiment of the present invention in which the sensing network consists of two groups of sensing interferometer means with similar sensor optical path delays and wavelength characteristics;

Figure 8 is a diagram of a preferred embodiment of the present invention in which the sensing network consists of two groups of sensing interferometer means with different sensor optical path delays but similar wavelength characteristics;

Figure 9 is a diagram of an embodiment of the present invention, in which optical fibres are used and the sensing network means is used in transmission;

Figure 10 is a diagram of an embodiment of the sensing interferometer means suitable for use in sensing network means when used in transmission; and

Figure 11 is a diagram of a preferred embodiment of the present invention which comprises of a broad band source means, a sensing

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first reflected part 25 and the second transmitted part 28 cannot interfere coherently.

Figure 3 is a diagram of an embodiment of the sensing interferometer means 10 constructed using optical fibre, in which wavelength filter means comprises a first wavelength selective coupler 30 and a second wavelength selective coupler 31 linked by an optical fibre 32 separated by a specified distance 33. An arm 34 of the first wavelength selective coupler 30 and of the second wavelength selective coupler 31 are terminated in mirrors 35 so that the length 33 and the lengths of the arms 34 constitute a sensor optical path delay. Incident electromagnetic radiation 36 is incident on the first wavelength selective coupler 30 and a first reflected part 37 is reflected by the mirror 35 of the first wavelength selective coupler 30 and a first transmitted part 38 is incident upon the second wavelength selective coupler 31. Similarly, a second reflected part 39 is reflected from the mirror 35 of the second wavelength selective coupler 31 and returns back along the optical fibre 32 and a second transmitted part 40 is transmitted through the first wavelength selective coupler 30.

Figure 4 is a diagram of an embodiment of part of the sensing network means in which two sensing interferometer means overlap. A first sensing interferometer means 42 and a second sensing interferometer means 43 are constructed such that the separation of the first reflection from the wavelength filter means of the first sensing interferometer means 42 and the second sensing interferometer means 43 are closer together than the sensor optical path 44 of the first sensing interferometer means 42 and the sensor optical path 45 of the second sensing interferometer means 43.

Figure 5 is a diagram of an embodiment of the reference interferometer means 7 taking the form of a Mach-Zehnder interferometer, and which includes a modulation means 50 in one of the optical paths. The modulation means 50 may be an acoustic optic modulator device, an optical fibre frequency shifter or an integrated optic frequency shifter for heterodyne signal processing. Alternatively the modulation means may be a phase modulator such as an electro-optic device or an optical fibre attached to a piezo-electric transducer for synthetic heterodyne technique.

Figure 6 is a diagram of an embodiment of the reference interferometer means 7 taking the form of a Michelson interferometer, and which includes a modulation means 50 in one of the optical paths. The modulation means 50 may be an acoustic optic modulator device,

length of optical fibre 23 and such that the length of fibre between the grating pairs 20 are made similar. The optical path delay in the sensing interferometer means 10 is determined by the time taken for the light to transverse the length of the optical fibre between the grating pairs 20. Each pair of in-line fibre gratings 20 select and reflect a distinguished band of wavelengths 11 emitted by the source means 1 such that the coherence of the selected light is much shorter than the optical path delay of the sensing interferometer means 10 and, therefore, the reflected optical signals are not coherent. The reflected light is transmitted to a reference interferometer means 7 where it is split in to two paths 130 and 131 which differ by a similar optical path delay of the sensing interferometer means 10. At the output of the reference interferometer means 7, the light signals are combined and a portion of consecutive reflected light signals which experience similar optical path delay interfere coherently with each other. For example, a portion of the first reflected light passed through the long path 131 of the reference interferometer means 7 interfere coherently with the portion of the subsequent reflected light passed through the short path 130 of the reference interferometer means 7. It is preferred to incorporate a modulation means 50, which may be a frequency shifter, in one of the paths of the reference interferometer for heterodyne detection where a carrier frequency is supplied by an oscillator source means 124. Alternatively, the modulation means 50 may an optical phase modulator to provide a means for synthetic heterodyne detection. At the output of the reference interferometer means 7, the band of wavelengths reflected 11 by each sensing interferometer means 10 are separated by a dispersive element 8 such as an optical grating and then imaged on to a photo-detector array 120 which converts the optical signals 121 in to electrical signals 122. The output of each photo-detector element 122 is fed to separate demodulators 123, which for frequency modulation detection may be phase-locked loops, to recover simultaneously the relative optical phase 125 induced in each sensing interferometer means 10.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and

CLAIMS

1. Apparatus for the measurement of one or more physical parameters, comprising source means for providing a source of electromagnetic radiation, sensing network means which comprises a plurality of sensing interferometer means each of which includes a wavelength filter means for selecting a band of wavelengths of electromagnetic radiation provided by the source means and is suitable for converting the magnitude of one or more physical parameters to a change in a sensor optical path length delay; a reference interferometer means for selecting a reference optical path delay; a wavelength selection means for selecting one or more of the band of wavelengths filtered by one or more of the sensing interferometer means; and detection means for converting the electromagnetic radiation selected by the wavelength selection means to an electrical signal.

2. Apparatus according to claim 1 in which the optical path delay of the sensing interferometer means is greater than the coherence length of the source mans, the coherence length of the electromagnetic radiation selected by each of the wavelength filter means, and the coherence length of the electromagnetic radiation selected by the wavelength selection means.

3. Apparatus according to claim 1 or claim 2 in which the sensing network means includes at least one optical fibre amplifier for amplifying or adjusting the relative power distribution of optical signals.

4. Apparatus according to claim 1 or claim 2 in which the wavelength filter means is a wavelength selective grating inside an optical fibre waveguide, a wavelength selective optical fibre coupler, or an integrated optic grating device.

substantially to each of the said narrow spectral bands to separate photodetector means, dependant on the wavelength of the said spectral band, such that detector means output signal responds to changes in optical path delay in the sensing interferometer means associated with the wavelength filter means of corresponding spectral transmission band.

9. Apparatus according to claim 8 in which the reference interferometer means contains optical phase or frequency modulation means in one or more of the optical paths in order to provide a periodic modulation signal on the optical detectors to facilitate electronic signal processing of the detected intensity to recover the information on path length changes in the sensing interferometer means.

10. Apparatus according to any one of the preceding claims and which is such that the source means and wavelength selection means are combined as a wavelength scanning source.